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STUDY OF HYDROGEN CONSUMPTION BY CONTROL SYSTEM IN PROTON EXCHANGE MEMBRANE FUEL CELL

(Kajian Penggunaan Hidrogen oleh Sistem Kawalan dalam Sel Bahan Api Membran Penukaran Proton)

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Abstract

Efficient operation results from a proper control strategy. In the operation and performance of a Proton Exchange Membrane Fuel Cell (PEMFC), the hydrogen gas flow rate is one of the most essential control parameter in addition to operating pressure, water management, temperature and humidity. This is because of the high cost and amount of energy are required to produce the purity hydrogen gas. In this paper, a Proportional Integral Derivative (PID) feedback control system is used to control the hydrogen flow rate. A strategy is adapted to balance the hydrogen use based on the loading requirements, especially during start-ups and sudden power demands. This system is implemented using National Instrument (NI) devices powered by the LabVIEW program. This is due to its simplicity and customization flexibility for measuring, processing and recording data. Designed structure allows the real-time implementation of a robust control law that is able to address the related nonlinearities and uncertainties without incurring a heavy computational load for the controller algorithm. While it facilitating a fast sampling rate according to the needs of the power system. Test results from the controller show that the new fuel control system provides good performance by reducing the amount of wasted hydrogen gas compared with that of the previous open loop system by 30 % to over 80 % saved by the varied load. This improvement is beneficial for any PEMFC that experiences fluctuating power demand, especially for vehicle applications.

Keywords: PEM fuel cell, proportional integral derivative, reactant controller, LabVIEW, national instrument

Abstrak

Operasi yang cekap terhasil dari strategi kawalan yang baik. Dalam operasi dan prestasi Fuel Cell Membran Penukaran Proton (PEMFC), kadar aliran gas hidrogen adalah salah satu parameter kawalan yang paling penting selain dari tekanan operasi, pengurusan air, suhu dan kelembapan. Ini kerana kos yang tinggi dan jumlah tenaga dikehendaki untuk menghasilkan gas hidrogen berketulenan tinggi. Dalam kertas kerja ini, sistem kawalan Perkadaran, Kamiran dan Perbezaan (PID) suap balik digunakan untuk mengawal kadar aliran hidrogen. Strategi disesuaikan untuk mengimbangi penggunaan hidrogen berdasarkan keperluan bebanan, terutamanya pada permulaan dan permintaan kuasa secara tiba-tiba. Sistem ini dilaksanakan dengan menggunakan peranti instrumen nasional (NI) yang dikuasakan oleh program LabVIEW. Ini kerana ia ringkas dan fleksibel untuk mengukur, pemprosesan dan rakaman data. Struktur yang direka bentuk membolehkan pelaksanaan masa sebenar hukum kawalan yang mantap yang mampu menangani keadaan yang tidak linear dan tidak menentu tanpa memerlukan pengiraan yang sukar untuk algoritma pengawal. Sambil itu, ia memudahkan kadar pensampelan yang cepat mengikut keperluan sistem kuasa. Hasil ujian dari pengawal menunjukkan bahawa sistem kawalan sel fuel yang baru memberikan prestasi yang baik dengan mengurangkan jumlah gas hidrogen yang terbazir berbanding sistem gelung terbuka dengan pengurangan sebanyak dari 30 % hingga 80 % pada variasi beban. Peningkatan ini memberi manfaat kepada mana-mana PEMFC yang mengalami permintaan kuasa turun naik, terutama untuk aplikasi kenderaan.

Kata kunci: Sel bahan api PEM, perkadaran, kamiran dan perbezaan (PID), pengawal bahan reaktan, LabVIEW, instrument nasional

Introduction

The proton exchange membrane fuel cell (PEMFC) generates energy from chemical sources to produce electrical energy efficiently and directly via an electrochemical reaction between the hydrogen and oxidant as the reactant. It has drawn enormous Research and Development (R&D) interest because its high energy density makes it the most viable candidate for use in the transportation, stationary power and portable device sectors [1]. PEMFC have the characteristics of low operating temperature, low noise, low weight, low corrosion, small volume and fast start-up capability, thus resulting in high energy density and quick start features.

However, the commercialization of this technology is still hampered by many challenges such as cutting costs, improving performance and increasing durability. Although those issues could be solved primarily by material selection, PEMFC performance relies mostly on design and operation of a fuel cell system. That includes a balance of plant, power converters and their control systems. System that commonly use are the humidity, reactant pressure, reactant flow rate, water, temperature and power electronics management systems [2, 3]. Every system plays a role in the design that will determine the correct amount of material that must be supplied for proper function and better electricity generation.

In this paper, study will focus on reactant system where the parameter should be considered for high performance; pressure, flow rate and stoichiometric ratio. To supply the reactant source three mode can be used; the dead-end mode, the flow-through mode and the recycling mode [4]. For the pressure factor, the amount supplied is depending on the size of stack. A higher value can increase the kinetics reaction in the electrochemical process. Thus, result in a higher power density and greater stack efficiency. Even so too high pressure will cause damage on the membrane electrode assembly (MEA) components. In the other hand, at low supplied pressure may result in a lower net available power. Therefore, its value should be sufficient in order to produce a required power and maintain the durability of fuel cell [5, 6]. Danzer et al. [7] prevent starvation issue of their stack operated at transient condition. They adjust the oxidant fuel by designing a controller that supplied a minimum pressure.

The flow rate and stoichiometric ratio are closely related. Higher flow rates cause the stoichiometric ratio and power production to become high as well because additional reactants are available for the reaction. However, this will reduce the energy production efficiency because more reactants are supplied but did not react and are wasted. Usually this happen when the fuel is supplied at a fixed and high stoichiometric ratio in orders to maintain the desired current density [8, 9]. But if the stoichiometric ratio is too low, will result in low performance [10, 11]. But problems often arise when the imposed loading varies and the supplied reactants are insufficient to produce the needed power. Zhou et al. [12] studies the behavior of fuel cell under fuel starvation condition. At different stoiciometric ratio and loading variation, they observe after unsatisfactory condition, the carbon corrosion issues arise.

This problem requires serious attention, especially in vehicle and load variation applications, because this complex phenomenon may cause a transient power issue that leads to performance degradation, damage to the electrode and electrolyte surface and shorter fuel cell life [13]. To solve this problem, a reactant controller should be implemented to control the flow rate supplied to the fuel cell stack. This is done to ensure an educate supply of reactant can be consume by fuel cell and generate the required power needed in both normal and transient operation mode. Flow control chosen to be control since it is critical parameter at uncertainties. This overview shows that a more efficient hydrogen-air supply management system is required for better PEMFC system operation to increase the efficiency of the reactant used.

In this paper, we focus on implementing a hydrogen fuel controller in which the design of a feedback control system using the PID controller was carried out to manipulate the supply to the fuel cell. But the fan speeds are maintained at a specific power for reduction of system complexity. A sufficient flow rate based on performance is determined to obtain the required reactant supply and to prevent excessive fuel consumption. This implementation can be broadly used in many applications that address load variation, such as electric vehicles in which the power demand is impulsive rather than constant.

Materials and Methods

System setup

PEMFC stack from Horizon Fuel Cell Technologies was used in this study. The open cathode stack was supplied with 99.99 % pure hydrogen gas that stored in compressed gas cylinder. The hydrogen gas flows inside the stack using a dead-end mode; every 10 seconds, the end valve was opened to release the existing gas for purging action. An axial fan are used to supply the oxygen source (air) using the flow-through mode. The overall setup tables for the experiment shown in Figure 1. This fuel cell can generate a variable power demand with a maximum rated value of 100 W (±14.4 V at ±7.2 A) and consists of 24 MEA cells with a total electrode area of 45 cm². The measurement of the stack performances are being varied using the DC electronic load and recorded by the NI data logger and LabVIEW program.

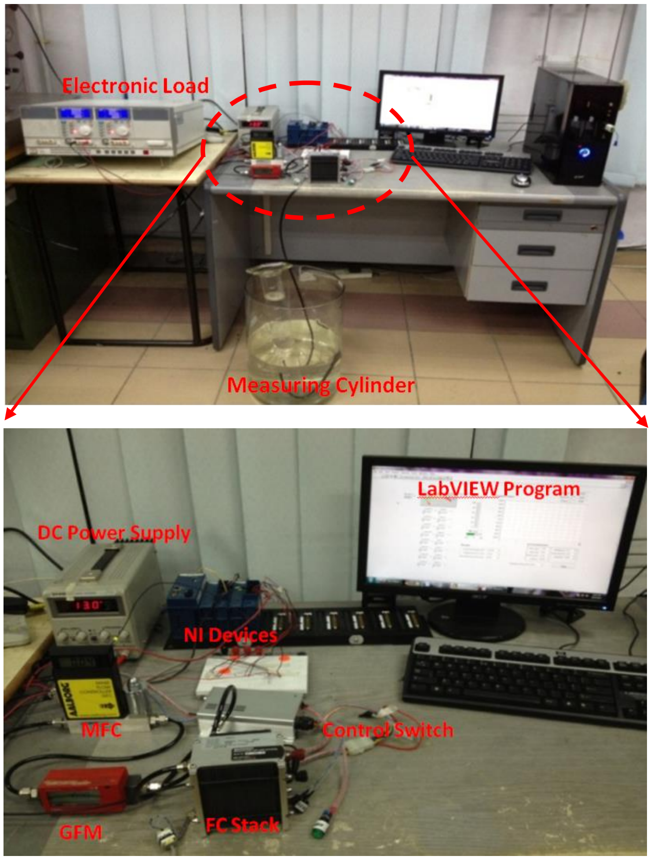

Figure 1. Overall table setup for testing PEMFC commercial stack

Fuel cells often use open loop system (OLS) shown Figure 2. In which hydrogen was supplied directly to the stack from compressed hydrogen gas stored in a cylinder tank in which the pressure are manually controlled with a pressure regulator. The procedures to operate the commercial stack with the OLS are based on flow diagram as in Figure 3. In this situation we need to make sure that the source of reactant are sufficient by supplying the flow rate in excess amount to avoid starvation problem.

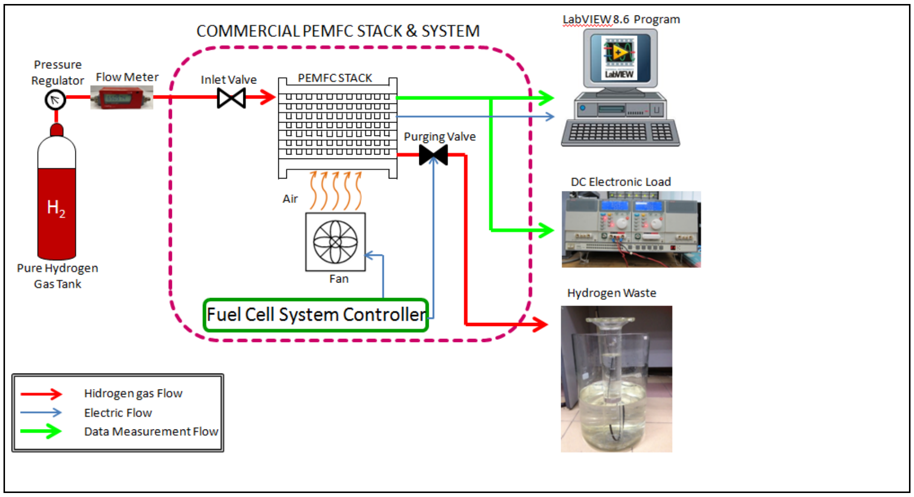

Figure 2. Flow diagram of operating the fuel cell stack using an Open Loop System (OLS)

However, the OLS system has the disadvantage where it will lead to starvation or waste of resources reactant when the flow rate is not controlled. Therefore, a hydrogen control system using PID control is built to reduce this problem. The application of controller functions in a manner similar to an automatic control system known as closed loop system (CLS). To see the hydrogen consumption difference for both systems; OLS without any modification and CLS with PID controller implemented used to manage the hydrogen flow rate when PEMFC generating the power.

An electrical circuit diagram build for the hydrogen flow rate control system shown in Figure 4. Electrical connection is made between 100 W commercial fuel cell stack, the DC power supply to turn on electronic equipment, mass flow controller (MFC) for the determination of the output and input current to change the flow rate of hydrogen, NI device (CFP-AIO-600) as connective reaction programmed in LabVIEW software and DC electronic load to monitor the voltage and power produce and also applied current load.

Control techniques

The PID controllers are used to improve fuel cell performance by regulating the amount of hydrogen using control element that exists in the LabVIEW program. The controller can provide control actions designed for the specific process requirements. The general form of PID is express as equation 1:

$$u(t) = K_p e(t) + K_I \int e(t)dt + K_D \frac{d}{dt} e(t) \qquad (1)$$

where the signal input (u) of the controller is equivalent to the increase in the proportion of (K_P) times the magnitude of the error plus the integral increase (K_i) times the integral of the error plus the increase in the difference (K_d) times the error difference.

For CLS, specific amounts of hydrogen are adjusted to a sufficient value by increasing and decreasing the delivery via a current control mode. This mode is based on the power required to maintain the stack output voltage, and this concept is vital to providing an efficient amount of power output and reducing hydrogen waste. To control this process, the signal must be subjected to these algorithms. The process begins by measuring the fuel cell system voltage output using a compact field point (cFP) hardware tool (read signal). The control program built using LabVIEW was used to measure the parameters, log the data, record the outputs and analyze the data to be applied to the fuel cell stack on a real-time basis. The results were subsequently passed to the cFP hardware tool (write signal) for implementation. A programmable electronic load was used to generate a pulse current load profile. These sequences were maintained and continued as the signal was sent out (control) and received (feedback) to analyze the system power.

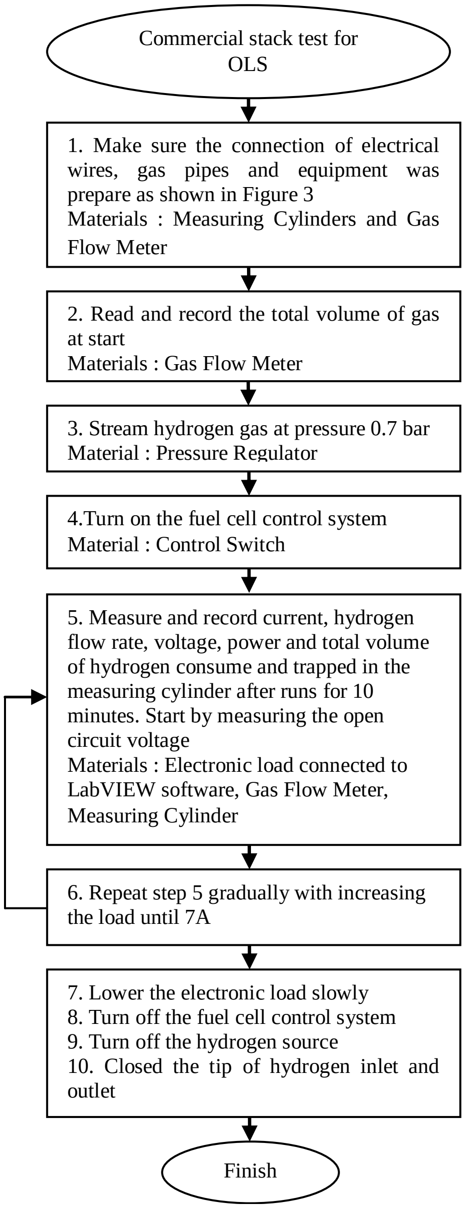

Figure 3. Flow chart of operating OLS

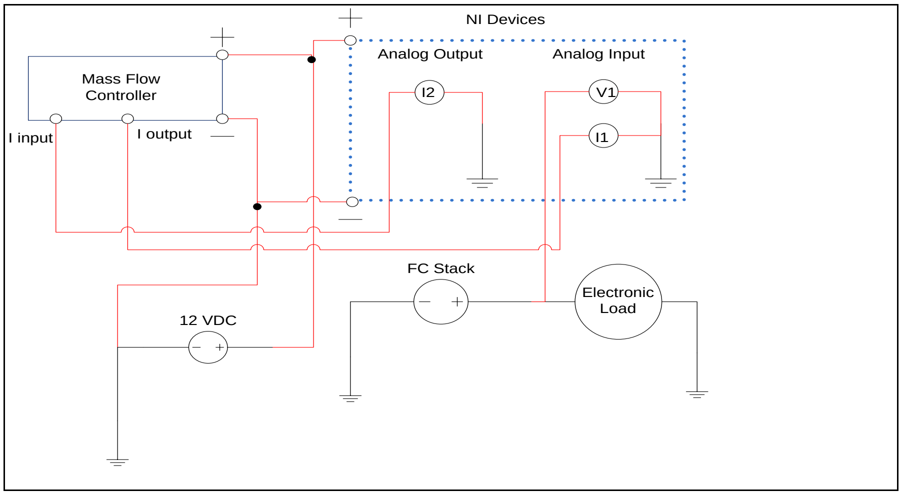

Figure 4. Hydrogen control system electrical circuit

In the CLS, adjustments are enacted using a hydrogen mass flow controller (MFC) functions to control the amount of hydrogen flow. The MFC is controlled by measurement and supply of a signal through the NI devices (cFP-AIO-600) based on the program built using LabVIEW. The setup of the system is shown in Figure 5.

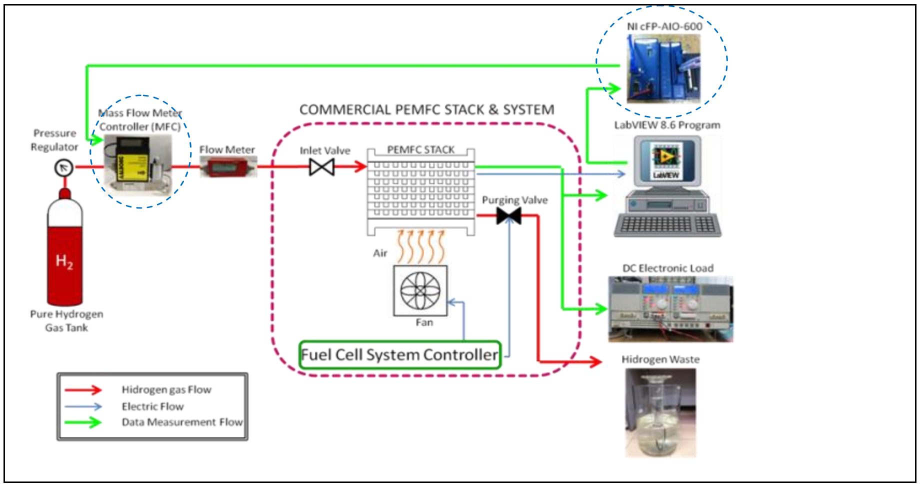

Figure 5. Flow diagram of the CLS

The NI module was placed between the fuel cell system and the computer (LabVIEW) to convert the analog input to a digital output for cFP measurements and control actions. A voltage range between 14 V (minimum voltage) up to 24 V (open circuit voltage) was determined to maintain suitable flow rates. The voltage was measured and the signal was logged using the NI analog input and subsequently sent to the LabVIEW controller program for processing. The required flow rate was automatically chosen using the PID program. The signal was sent back using the NI analog output current to control the MFC valve flow rate. The program reactions are based on PID changes that produce an operating signal that manipulates the flow rate of the hydrogen reactant to maintain the stack output voltage.

The flow rates required were determined from the OLS results and aimed to conserve hydrogen based on the loading demand to maintain the fuel cell stack voltage. Eight sets of voltage ranges were fixed to comply with the different flow rates at the transient conditions. The detailed voltage ranges, flow rates and MFC output currents are listed in Table 1. The procedures to operate the CLS are also listed as in Figure 6. The developed PID controller program details structure are shown in the block diagram in Figure 7.

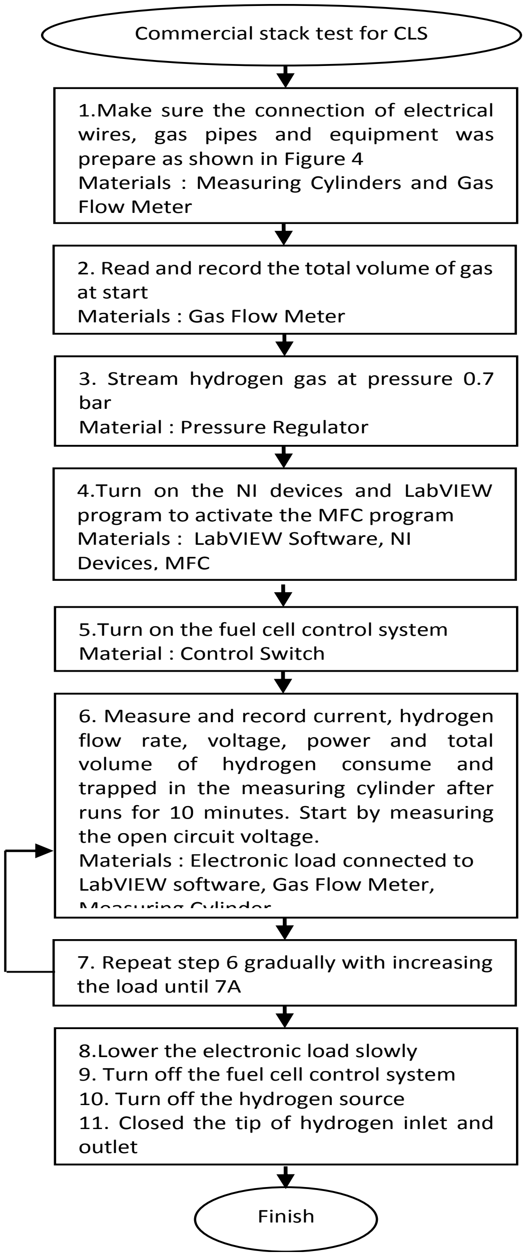

Figure 6. Flow diagram of the CLS

Table 1. Voltage range options at different hydrogen flow rates for controller calibration

Range Option	**Stack Voltage Range (V)**	**Hydrogen Flow Rates (l/min)**	**cFP AIO 600 Output Current to MFC (A)**
1	24.0 – 22.0	0.01	0.0044
2	22.0 – 20.0	0.35	0.0046
3	20.0 – 18.5	0.52	0.0049
4	18.5 – 18.0	0.72	0.0052
5	18.0 – 17.4	0.83	0.0054
6	17.4 – 16.5	0.98	0.0057
7	16.5 – 15.5	1.23	0.0061
8	15.5 – 14.0	1.41	0.0064

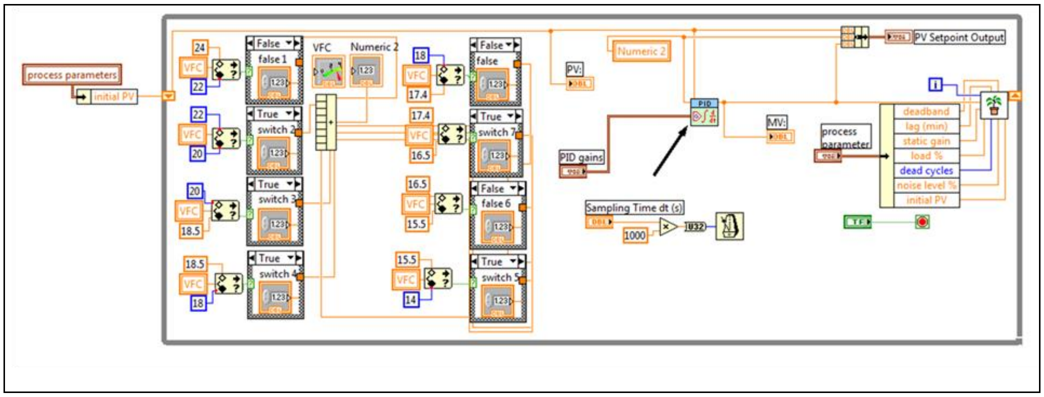

Figure 7. Block diagram interface of the PID control system

Results and Discussion

Stack performance in different systems

As the main part of this study, a flow rate controller was implemented for more reliable operation using CLS. The strategies used then were compared with the OLS and controller used by Kim et al. [14]. Kim et al. using a PEM fuel cell stack can power up to 150-W and implement a closed-loop method controller. The effects on the fuel cell system performance in response to hydrogen reactant control were analyzed. Figure 8 shows the performance comparison between them, where Figure 8a indicates that the implementations of controlled hydrogen flow rates are able to satisfy the power demand.

The performance response at different loadings shows the values of the hydrogen consumption rates are affected. Where, as the power stack demand is increasing, the hydrogen flow rates consumed also increase, but the value consumed different depends on the system used. In Figure 8b, can be observe that the demand of hydrogen are lower request by the CLS compared to the two other system. Therefore, it is necessary to consider hydrogen control management in the fuel cell design in order to reduce hydrogen usage. After ensuring control of the hydrogen supply does not affects the power performance, the impact of hydrogen consumption and wasted (purged out) will further studied for both the OLS and CLS processes.

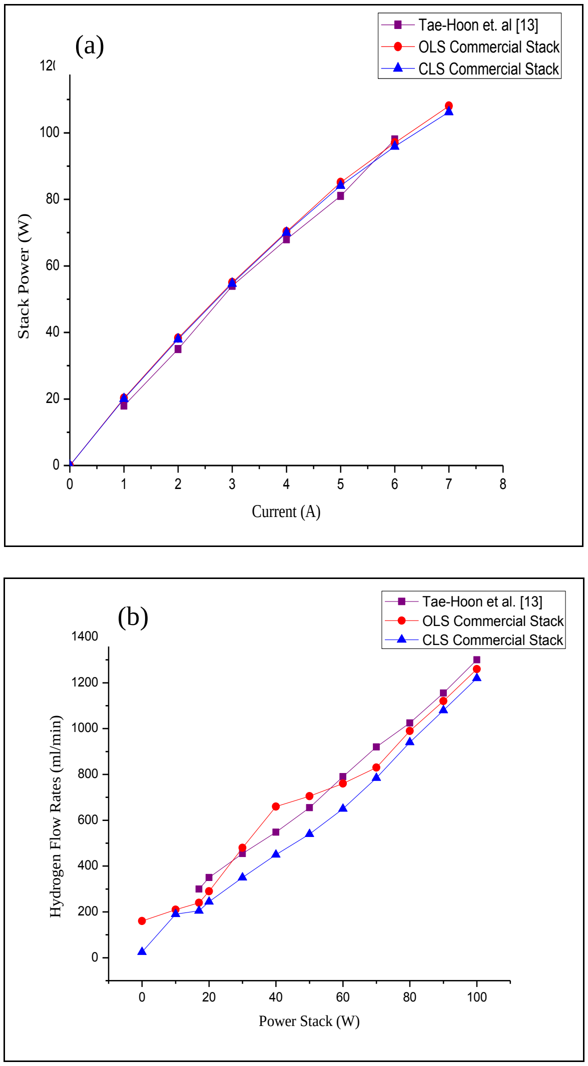

Figure 8. Characteristics of (a) stack power and (b) hydrogen flow rate under various loading values at different stack conditions

Control system impact in hydrogen consumption

The data of overall performance shows that the amount of hydrogen consumes are directly proportional to the load demand. Figures 9 indicate that the volumes of hydrogen that flowed into the stack were consumed and were subsequently purged out of the fuel cells every 10 minutes differed with respect to the loading value.

An increase in loading also increased the amount of hydrogen that entered the fuel cell; for the OLS in Figure 9, almost 2 liters of hydrogen was wasted at low currents from the OCV until a current of 4 A was reached because of the purging condition. However, the amount of wasted hydrogen decreased as the loading increased, which indicates that additional hydrogen reacts at a higher demand. Between 5 A and 7 A, the purging value increased to greater than 2 liters. The CLS showed an almost identical pattern to that previously discussed for the OLS. The load and hydrogen influx were positively correlated, but the influx was limited by the controller. Thus, the purged amounts of hydrogen were smaller compared with those of the OLS, and thus, the CLS constitutes an improvement by gradually and appropriately allowing hydrogen to enter the fuel cell. Hydrogen purged out recorded between 30% to over 80% have been successfully saved depends on the applied load.

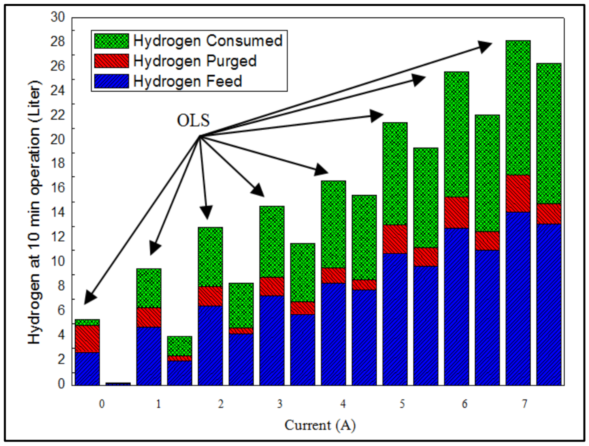

Figure 9. Total hydrogen consumption for OLS and CLS configuration

Transient loading effect

The study continues with an application of a variable load to observe the effect on the performance and use of hydrogen flow control and to determine whether it can produce effective results for the active load current changes. The load current for this stack can vary depending on the load demand, from 0 A to 7 A, and the changes cover all of the stack operations. In this implementation, the patterns in the current changes are set to distinguish the results from the system used. Figure 10 shows the change in current fluctuations applied manually via an electronic load. These changes cover nearly the entire fuel cell stack operating conditions.

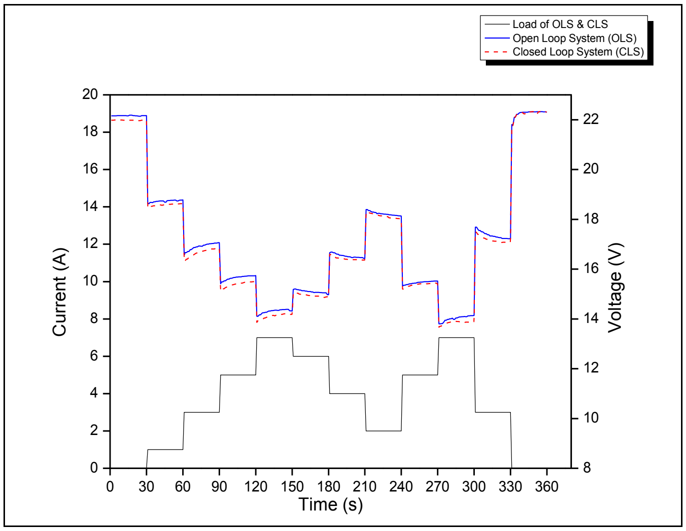

Figure 10. Stack performance at variation loading for OLS and CLS vs. time

The performance of load variation at both conditions operate at 360 second can be observed in Figure 10. The amount of hydrogen flow used by the commercial stack for the OLS is 4.90 liters with 1.30 liters wasted. However, for the CLS condition, only 4.20 liters were used and 0.67 liters were released into the atmosphere. This result shows that almost 50% of the hydrogen waste has been eliminated. The designed controller produced more optimal power efficiency in terms of fuel consumption. This result shows that the new system improved the fuel cell system efficiency in terms of fuel consumption and cost effectiveness by reducing the waste of hydrogen resources released into the atmosphere.

Conclusion

The impact of hydrogen consumption in both the open-loop and closed-loop operations was compared to validate the proposed design. The controlled flow rates mimicked those of the OLS, and this system was most beneficial at the purging condition. The power performance of the CLS control system result was the same as that of the previously established OLS. The implementation effectively controlled the hydrogen flow rate under active current load variations such that minimal amounts of hydrogen were wasted while accommodating the needs of the reaction. Although this experiment used small-scale and commercialized fuel cells, with short time of operation indicated that the CLS improved the fuel cell hydrogen efficiency and cost effectiveness by reducing waste, which constitutes a significant benefit to the commercial fuel industry. The newly proposed fuel cell control system is also able to accommodate transient load demands. A sufficient hydrogen supply maintains fuel cell performance, reduces fuel waste and prevents MEA damage. If this condition is applied to higher power fuel cells or is implemented for longer durations, additional hydrogen can be conserved.

Acknowledgement

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